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"COMMINUTION OF AEOLIAN MATERIALS ON MARS"

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by

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Summary:

The research task had a two-year performance period for the investigation of aeolian processes on Mars. Specifically, we were investigating the comminution of sand grains as individual particles, and as bulk populations. Laboratory experiments were completed for the individual particles, and results led to a new theory for aeolian transport that is broadly applicable to all planetary surfaces. The theory was presented at the LPSC and the GSA in 1998 and 1997 respectively. Essentially, the new theory postulates that aeolian transport is dependent upon two motion thresholds—an aerodynamic threshold and a bed-dilatancy threshold. The latter mechanism had not been previously recognized, but it implies that transport of sand on Mars is fundamentally different from that on Earth. In particular, transport flux on Mars should be much higher than predicted. Also, results from the experiments indicate that the grain velocities on Mars should lead to rapid self-destruction of particles in transport, as predicted by the kamikaze theory of Sagan—it was in fact, one of the objectives of the research to test this hypothesis. Both the high flux and high comminution rates combined lead to a dilemma: both experiment and theory are in conflict with the evidence for vast dune fields on Mars. The conclusions that might be drawn are that the dunes are actually relict structures, that the sand supply is extremely rapid by geological standards, or that our current understanding of the Martian environment is much too immature to enable reasonable simulations, i.e., there could be some completely unknown variables. The experiments on the bulk behavior of sand are continuing after a hiatus caused by various factors relating to the investigators and to the machinations of the NASA system in 1998.

Publications (see attached):

- (1) Marshall, J. Towards a theory for planetary aeolian transport. *Geophys. Res. Lett.* In prep. (1998).
- (2) Marshall, J., Borucki, J., & C. Bratton. Aeolian sand transport in the planetary context: Respective roles of aerodynamic and bed-dilatancy thresholds, *LPSC*, XXIX, 1131 (1998).
- (3) Marshall, J. Unique Aeolian Transport Mechanisms On Mars: Respective roles of percussive and repercussive grain populations in the sediment load. *GSA*, A-214 (1997).
- (4) Marshall, J., Borucki, J., & Sagan, C. Behavior of windblown sand on Mars: Results from single-particle experiments. *LPSC XXVII*, 813 (1996).

AEOLIAN SAND TRANSPORT IN THE PLANETARY CONTEXT: RESPECTIVE ROLES OF AERODYNAMIC AND BED-DILATANCY THRESHOLDS. J.R. Marshall¹, J. Borucki², and C. Bratton¹, ¹SETI Institute, NASA Ames Research Center, MS 239-12, Moffett Field, CA 94035-1000, ²NASA Ames Research Center.

The traditional view of aeolian sand transport generally estimates flux from the perspective of aerodynamic forces creating the airborne grain population, although it has been recognized (1) that "reptation" causes a significant part of the total airborne flux; reptation involves both ballistic injection of grains into the air stream by the impact of saltating grains as well as the "nudging" of surface grains into a creeping motion. Whilst aerodynamic forces may initiate sand motion, it is proposed here that within a fully-matured grain cloud, flux is actually governed by two thresholds: an aerodynamic threshold, and a bed-dilatancy threshold. It is the latter which controls the reptation population, and its significance increases proportionally with transport energy. Because we only have experience with terrestrial sand transport, extrapolations of aeolian theory to Mars and Venus have adjusted only the aerodynamic factor, taking gravitational forces and atmospheric density as the prime variables in the aerodynamic equations, but neglecting reptation.

The basis for our perspective on the importance of reptation and bed dilatancy is a set of experiments that were designed to simulate sand transport across the surface of a Martian dune. Using a modified sporting crossbow in which a sand-impelling sabot replaced the bolt-firing mechanism, individual grains of sand were fired at loose sand targets with glancing angles typical of saltation impact; grains were projected at ~80 m/s to simulate velocities commensurate with those predicted for extreme Martian aeolian conditions (2). The sabot impelling method permitted study of individual impacts without the masking effect of bed mobilization encountered in wind-tunnel studies. At these Martian impact velocities, grains produced small craters formed by the ejection of several hundred grains from the bed. Unexpectedly, the craters were not elongated, despite glancing impact; the craters were very close to circular in planform. High-speed photography showed them to grow in both diameter and depth after the impactor had ricocheted from the crater site. The delayed response of the bed was "explosive" in nature, and created a miniature ejecta curtain spreading upward and outward for many centimeters for impact of 100-300 micron-diameter grains into similar material. Elastic energy deposited in the bed by the impacting grain creates a subsurface stress regime or "quasi-Boussinesq" compression field (Figure 1). Elastic recovery of the bed occurs by dilatancy; shear stresses suddenly convert the grains from closed to open packing, and grains are consequently able to eject themselves forcefully from the impact site. Random jostling of the grains causes radial homogenization of stress vectors and a resulting circular crater. There is a great temptation to draw parallels with cratering produced by meteorite impacts, but a rigorous search for common modelling ground between the two phenomena has not been conducted at this time.

For every impact of an aerodynamically energized grain, there are several hundred grains ejected into the wind for the high-energy transport that might occur on Mars. Many of these grains will themselves become subject to the boundary layer's aerodynamic lift forces (their motion will not immediately die and add to the creep population), and these grains will become indistinguishable from those lifted entirely by aerodynamic forces. As each grain impacts the bed, it will eject even more grains into the flow. A cascading effect will take place, but because it must be finite in its growth, damping will occur as the number of grains set in motion causes mid-air collisions that prevent much of the impact energy from reaching the surface of the bed -- thus creating a dynamic equilibrium in a high-density saltation cloud.

It is apparent from Figure 1 that for a given impact energy, the stress field permits a smaller volume of grains to convert to open packing as the size of the bed grains increases, or as the energy of

the "percussive" grain decreases (by decrease in velocity or mass). Thus, the mass of the "repercussive" grain population that is ejected from the impact site becomes a function of the scale of the stress field in relation to the scale of the bed material (self-similarity being applicable if both bed size and energy are simultaneously adjusted). In other words, in a very high energy aeolian system where an aerodynamically raised grain can ballistically raise many more grains, the amount of material lifted into the wind becomes largely a function of a dilatancy threshold. If this threshold is exceeded, grains are repercussively injected into the saltation cloud. The "dilatancy threshold" may be defined in terms of the saltation percussive force required to convert the bed, through elastic response, from a closed to an open packing system. If open packing cannot be created, the grains cannot escape from the impact site, even though the elastic deformation and percussive force may be able to reorganize the grains with respect to one another. As the crossbow experiments showed, for an ever-increasing bed grain size, a point is reached when no material can be moved because the energy of the percussive grain is insufficient to dilate the relatively coarse bed. Although this seems to be stating the obvious -- that too little energy will not cause the bed to splash -- the consequences of exceeding the "splash threshold" by dilatancy are not so obvious for high-energy aeolian transport. It is noted that the force required to elastically dilate the bed has to overcome Coulombic grain attractions such as dipole-dipole coupling, dielectric, monopole, contact-induced dipole attractions, van der Waals forces, molecular monolayer capillary forces, as well as the mechanical interlocking frictional resistance of the grains.

On Mars, it is predicted that the dilatancy threshold may be the prime control of grain flux. On earth, the aerodynamic thresholds and dilatancy thresholds are of about equal importance (1). On Venus, the aerodynamic threshold dominates (Figure 2). Thus, aeolian transport of sand in the planetary context should be viewed as a variable combination of primarily these two thresholds, not simple a function of an aerodynamic threshold adjusted for gravity and atmospheric density.

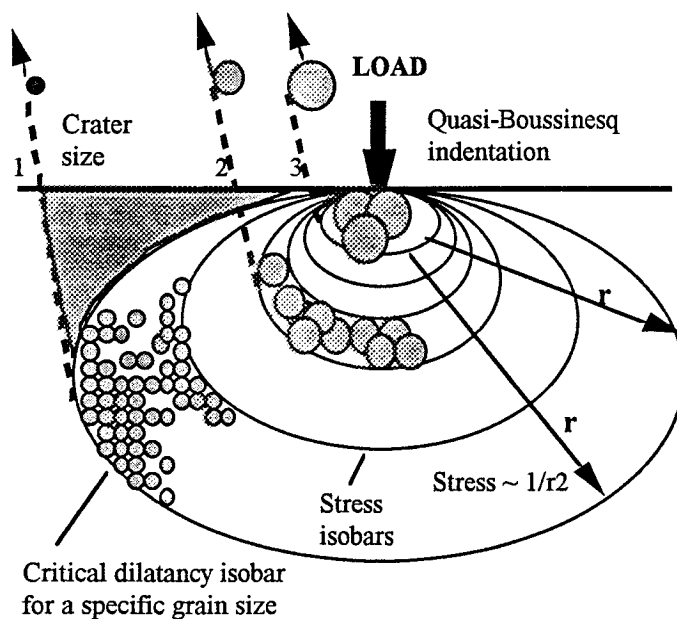


Figure 1: Relationship of stress field magnitude to dilatable bed volume

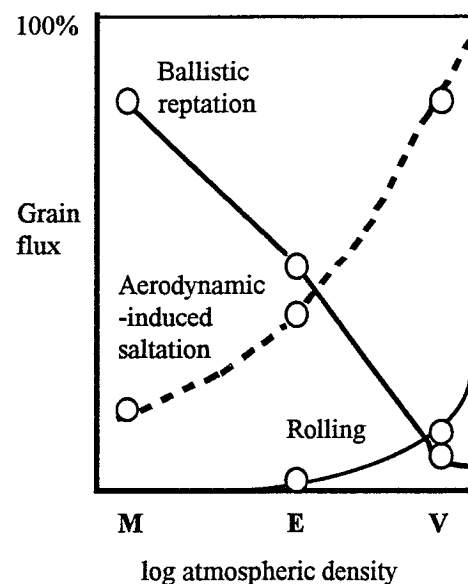


Figure 2: Relative roles of flux modes for Mars, Earth, & Venus

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(1) Anderson R.S. (1987) Document BB-56, Univ. Washington. (2) Sagan C. (1973) JGR 78, 4155.

UNIQUE AEOLIAN TRANSPORT MECHANISMS ON MARS: RESPECTIVE ROLES OF
PERCUSSIVE AND REPERCUSSIVE GRAIN POPULATIONS IN THE SEDIMENT LOAD

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Experiments show that when sand-size grains impact a sediment surface with energy levels commensurate for Mars, small craters are formed by the ejection of several hundred grains from the bed. The experiments were conducted with a modified crossbow in which a sand-impelling sabot replaced the bolt-firing mechanism. Individual grains of sand could be fired at loose sand targets to observe ballistic effects unhindered by aerodynamic mobilization of the bed. Impact trajectories simulated the saltation process on dune surfaces.

Impact craters were not elongated despite glancing (15 deg.) bed impact; the craters were very close to being circular. High-speed photography showed them to grow in both diameter and depth after the impactor had ricocheted from the crater site. The delayed response of the bed was "explosive" in nature, and created a miniature ejecta curtain spreading upward and outward for many centimeters for impact of 100-300 μ m-diameter grains into similar material. This behavior is explained by deposition of elastic energy in the bed by the "percussive" grain. Impact creates a subsurface stress regime or "quasi-Boussinesq" compression field. Elastic recovery of the bed occurs by dilatancy; shear stresses suddenly convert the grains to open packing and they consequently become forcefully ejected from the site. Random jostling of the grains causes radial homogenization of stress vectors and a resulting circular crater. A stress model based on reperlussive bed dilatancy and interparticle adhesive forces (for smaller grains) predicts, to first order, the observed crater volumes for various impact conditions.

On earth, only a few grains are mobilized by a percussive saltating grain; some grains are "nudged" along the ground, and some are partly expelled on short trajectories. These motions constitute reptation transport. On Mars, saltation and reptation become indistinct: secondary or "reperlussive" trajectories have sufficient vertical impulse to create a dense saltation population of many tens or hundreds of grains for each single high-speed saltation perlussion of the bed. Impact cascading will lead to near-surface distortion of the boundary layer, and choked flow formed by a dense "slurry" of sand, with the majority of grains mobilized by reperlussive forces rather than by aerodynamic lift. This proceeds until a fully-matured transport layer imposes self-limitations as grain-population density constrains the free-path motion of individual grains.

BEHAVIOR OF WINDBLOWN SAND ON MARS: RESULTS FROM SINGLE-PARTICLE EXPERIMENTS; J.R. Marshall¹, J. Borucki², and C. Sagan³,

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Experiments are investigating the behavior of individual sand grains in the high-energy Martian aeolian regime. Energy partitioning during impact of a saltating grain determines grain longevity, but it also influences the way in which the bed becomes mobilized by reptation. When single grains of sand are fired into loose beds, the bed can absorb up to 90% of the impact energy by momentum transfer to other grains; it has been discovered that the impacting grains cause circular craters even at low impact angles. Hundreds of grains can be splashed by a single high-velocity (100 m/s) impact causing more bed disturbance through reptation than previously thought. The research is supported by NASA's PG&G Program.

Because the Martian aeolian environment in both high energy and of long duration, the most mobile fractions of windblown sand should have eradicated themselves by attrition, unless sand supply has kept pace with destruction. It is therefore important to understand the rate of grain attrition in order to make sense of the existence of vast dune fields on Mars. Attrition has been addressed in other studies, but precise data for a single saltating grain striking a loose bed of sand have not been acquired—the quintessential case to be understood for dunes on Mars.

To acquire these data, we are employing a compound crossbow which has the bolt-firing mechanism replaced with a pneumatically-automated sabot system. The sabot can launch individual grains of sand of any size between several millimeters and ~ 50 microns, at velocities up to 100m/s. This is around the maximum velocity expected for saltating grains on Mars. The sabot sled is equipped with photoelectric sensors for measuring shot velocity. Baffling of the grain's exit orifice has enabled projection of single grains without significant aerodynamic effects from the sabot. Grains are fired into loose beds of sand at about 15 degrees from the horizontal (typical saltation trajectory at impact) while being filmed on high-speed video. High-intensity pulse illumination for the grains is triggered by the solenoid-operated bow trigger. A 45 degree mirror over the impact site provides simultaneous horizontal and vertical images of the impact on each video frame. UV fluorescence is enabling grain and grain-fragment recovery.

At 100 m/s, grains of all sizes shatter into many fragments when the sand is replaced with a solid target. Kinetic energy of the grains at this velocity exceeds the critical energy for catastrophic failure of minerals. Although probably exceptional as a grain speed, it suggests that conditions on Mars might elevate materials into an attrition regime not encountered on other planets; individual grains blown across rock pavements on Mars will have short lifespans. When experimental grains impact loose (dune) sand, much, if not most of the kinetic energy is converted into momentum of other grains. Using high-speed filming, the energy involved in splashing grains at the impact site can be derived from the size of the crater, the speed of the splashed grains, and the rebound speed of the impactor. The amount of energy partitioned into material failure (as opposed to momentum) is too small a fraction of the total to be calculated under these circumstances. This does not necessarily mean that little damage occurs to the grains (the full extent of the damage has yet to be determined) because only a small fraction of the impact energy is required for inducing brittle fracture. Damage is orders of magnitude less than during impact against solid surfaces.

In the process of video-imaging the impact of single grain into sand, it was found that impact crater were always symmetrical (no elongation in the direction of impact). This is surprising for 15 degree trajectories, and distinctly reminiscent of (but not analogous to) meteorite craters. Many hundreds of grains are injected into the air by one single high-velocity grain; the ejecta blanket covers several square centimeters even with the impact of a 100 micron particle. Every grain can trigger the entrainment of a significant portion of the bed, enough material in fact, to account for much of the grain population at the base of a saltation cloud.